



A STATUS REPORT ON THE PRINTED MOTOR

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Presented at
AIEE General Meeting
New York, New York
Winter 1962



Photocircuits

CORPORATION

GLEN COVE, N. Y. / ANAHEIM, CALIF.

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Introduction

Three years ago the essential features of the printed circuit DC motor were described at the AIEE Winter General Meeting. Since that time much progress has been made in technical areas and considerable insight has been gained into the general properties and uses of the device. This report is intended to review the current status of the printed circuit DC motor and to develop a better picture of what sort of machine has been brought into existence by means of the new technique.

We may review the essential features of the device by reference to Figure 1 which is an exploded view of one of the motors as they are currently being manufactured. It will be recalled that the most significant feature of the motor is the disc shaped armature containing no iron which is produced by printed circuit techniques and which revolves in a flat air gap perpendicular to the shaft. Many of the properties originally ascribed to the motor are derived from the fact that the rotating structure contains no iron; more particularly, the smoothness of the generated torque or absence of cogging and preferred armature positions. In the original discussions we noted that a high speed of response to changes in terminal voltage was to be expected from the structure because of the low inertia of the rotating armature. We also pointed out that superior commutation characteristics could be expected because of the low armature inductance, and that the electrical time constant of the machine was small.

The passage of three years has represented the accumulation of sufficient experience so that a condensation of the current state of the art into a brief report presents a substantial problem. On considering the matter, it appears most desirable to approach the subject from five different points of view. To this end we shall discuss:

1. The most important properties of the printed motor as distilled from application experience.
2. The ranges of machine sizes and ratings which have been explored to date.
3. Operating experience on lifetime and reliability.
4. Unique properties of the motor which have proven to be of interest.
5. Types of applications in which printed motors are currently used.

Most Important Properties

The printed motor produces an extremely uniform torque in response to a constant current, combined with the ability to operate at speeds ranging from zero to several thousand revolutions per minute. The machine displays no tendency whatever toward preferred armature positions together with a low mechanical time constant. Electro-mechanically, the motor operates according to straight line speed-

Figure 1

Exploded view of a printed motor showing the magnet structure, disc-like armature and flux return plate. Brushes bear directly on the winding through the return plate structure.

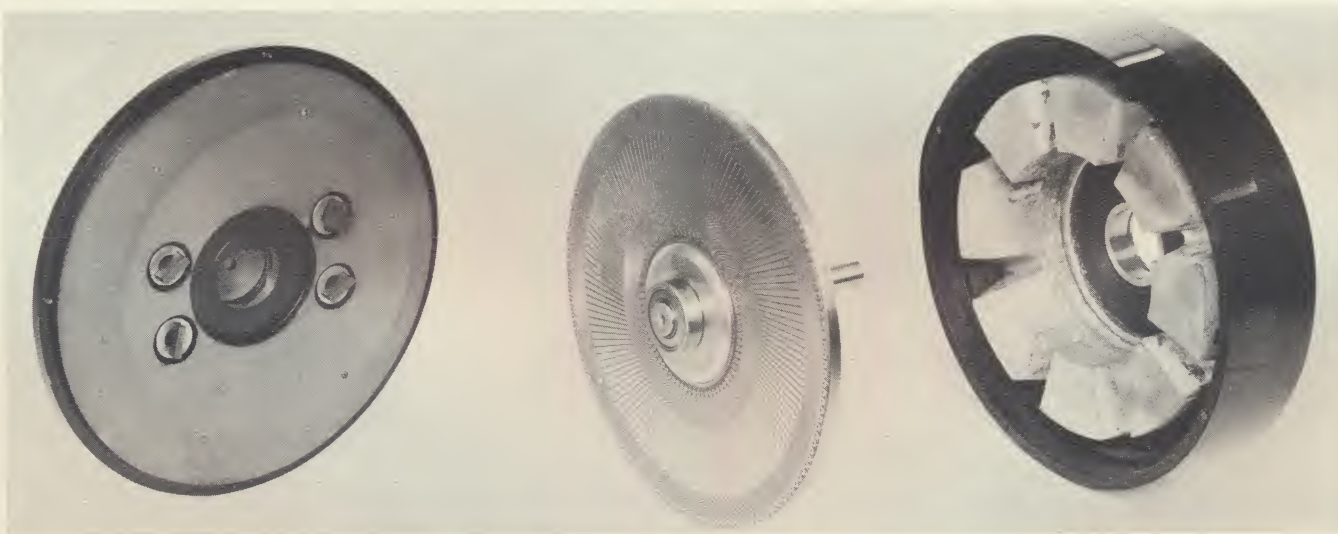
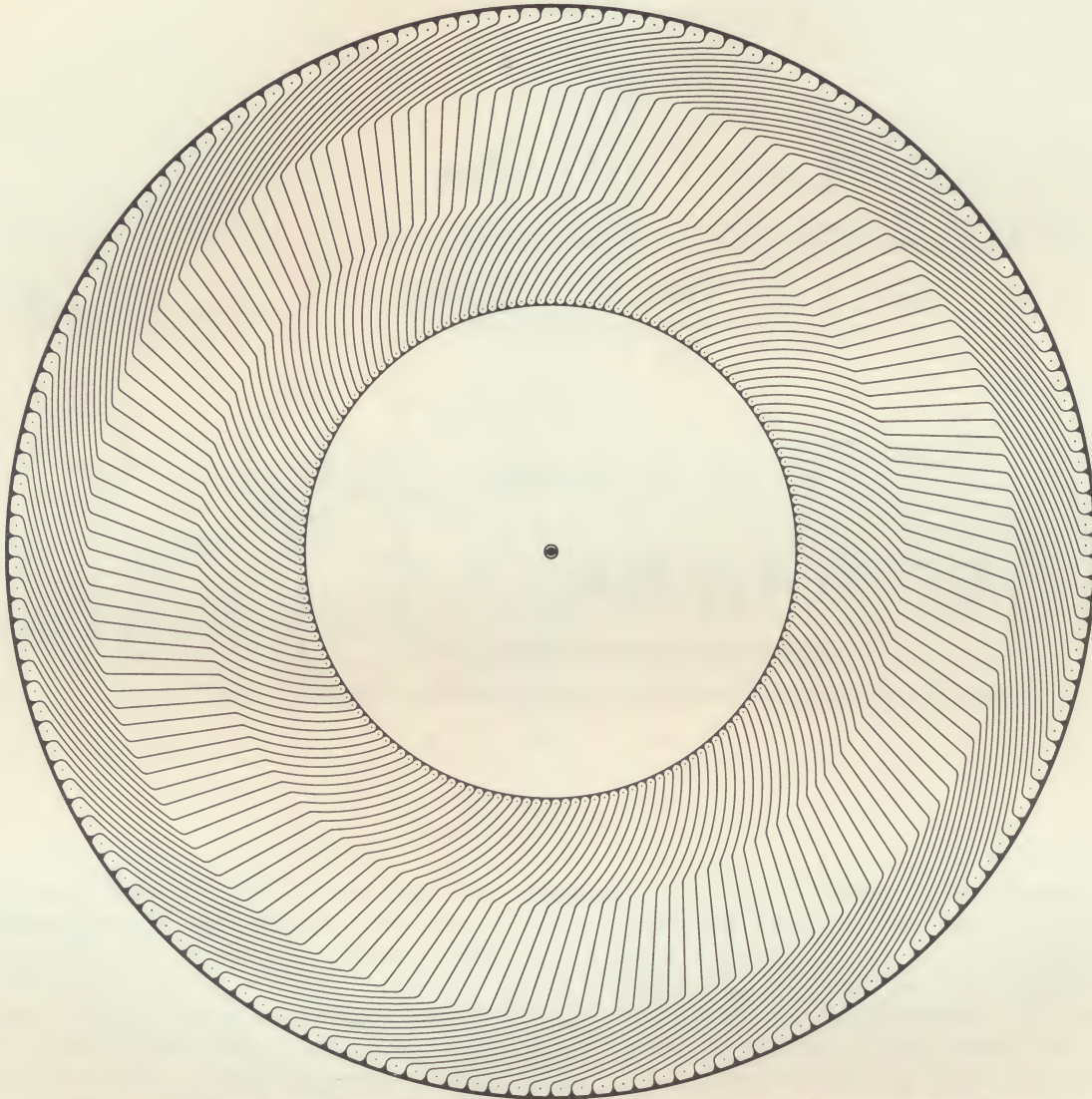


Figure 2

Drawing of armature circuit pattern for an 8 pole wave winding. Each side of the winding is identical in appearance. Connections from side to side are made automatically by plated-through holes.



torque characteristics while the armature inductance is so low that the motor input impedance at stall conditions is essentially resistive. In short, the motor appears to combine many of the desirable characteristics of both a torque motor and a fast response high speed servomotor into one machine.

A careful consideration of these statements will show that the printed motor closely approaches an ideal servomechanism component, particularly for high precision or fast response applications in which the motor is directly connected to the load shaft without intermediate gearing.

Machine Sizes and Ratings

Because of the printed motor geometry, the various machine parameters and permissible ratings vary at a rapid rate with the dimensions of the structure. If we relate all linear dimensions of any two geo-

metrically similar motors by a factor k while holding the number of armature conductors and the flux density constant, we find that:

Continuous rated torque varies as $k^{3.5}$;

Torque per ampere varies as k^2 ;

Induced EMF at constant speed varies as k^2 ;

Armature resistance varies as k^{-1} ;

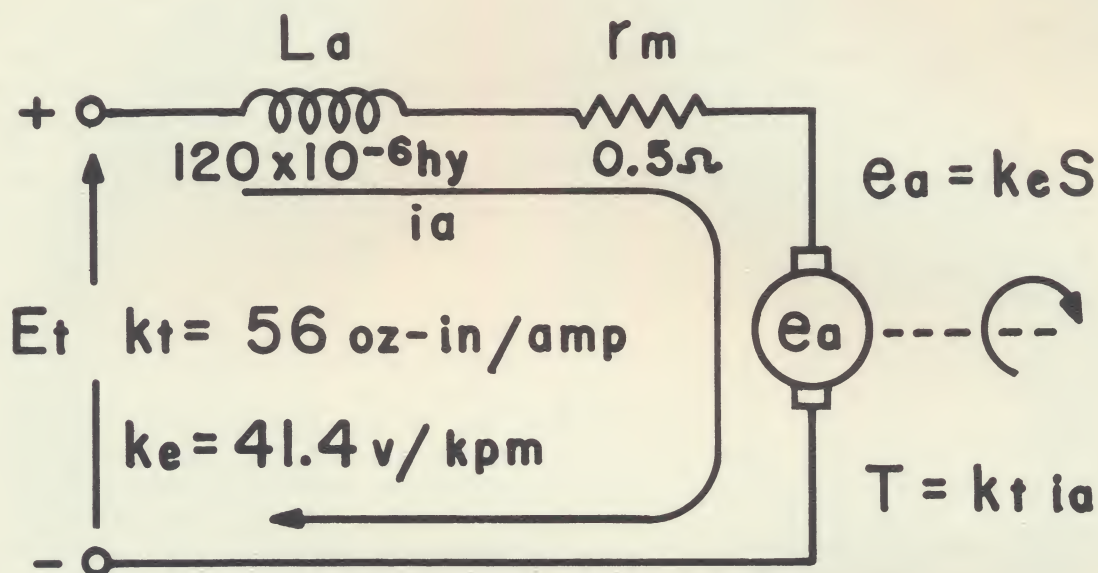
The slope of the speed torque curve or the equivalent mechanical source resistance varies as k^{-5} ;

Mechanical time constant is invariant;

and similar relations.

Figure 3

Complete electrical equivalent circuit diagram of a Model PM-1028 printed servo motor. Note the small value of series armature inductance.



These "similitude laws" indicate that a substantial increase in performance and ratings over some reference machine may be achieved for only a moderate increase in dimensions. Conversely, they show that some lower limit of dimensions will be rapidly attained at which the motor ratings cease to be of practical interest.

For this reason, the smallest printed motor presently in production utilizes an armature disc having a diameter of 3.6 inches. The machine carries the designation PM-368, and will develop a torque of 12 oz.-in. under continuous duty at a maximum speed of 4000 rpm. A pulse torque of 150 oz.-in. is permissible. The armature resistance is 0.63 ohms and the motor develops 3.0 oz.-in. per ampere of armature current.

Application of the similitude laws will show that a motor having an armature diameter of, say, 1.8 inches, or half that of the type PM-368, would hardly develop enough torque to overcome its own brush friction, since the permissible torque would be 11.3 times less ($2^{3.5}$) or only about 1 oz.-in.

In contrast, the type PM-1028, having an armature diameter of 10.2 inches, will develop 1000 oz.-in.

continuously at 1500 rpm with a pulse capability of 8400 oz.-in. or 43.7 lb.-ft.

A detailed listing of various printed motor types is given in Table I. The models shown include six standard production units, a number of special types, and one machine (the largest) which is still in the design stage. A close inspection of the tabulation will disclose a number of interesting performance attributes.

Experience to date does not suggest any definite upper limit to the dimensions or ratings of printed armature type machines. It is certainly obvious that the manufacturing techniques contemplated for the type PM-5008-C (50 inches armature diameter) are different from those now used for the PM-368 and other similar motors; yet no basic problems are encountered. The only restriction on ratings which appears desirable as the motor diameter increases applies to the maximum operating speed. Mechanical considerations dictate that the rotational velocity should be reduced as a function of diameter for evident reasons. We are currently guided by the relationship

$$S = 50 / D^{1.5}$$

MOTOR TYPE NUMBER PM-	RATED TORQUE - OZ-IN	MAXIMUM PULSE TORQUE - OZ-IN	MECHANICAL TIME CONSTANT - OZ-IN	EQUIVALENT MECHANICAL IMPEDANCE-RPM/OZ-IN	RATED SPEED - RPM	RATED CURRENT - AMPERES	NUMBER OF ARMATURE CONDUCTORS	ARMATURE RESISTANCE - OHMS	NO-LOAD FRICTION TORQUE - OZ-IN	TORQUE PER AMPERE - OZ-IN/AMPERE	BACK EMF PER 1000 RPM - VOLTS	DIAMETER - INCHES	AXIAL LENGTH - INCHES	WEIGHT - POUNDS	NOTES
368	12	150	34	85.0	4000	7.3	97	0.63	1.5	3.0	2.22	4.250	2.250	3.0	General purpose servo motor
386-HF	30	150	13	24.8	4000	7.3	97	0.63	5.2	5.9	4.35	5.625	5.516	18.5	High performance servo motor
368-HF-II	30	150	1.8	5.8	300	7.3	97	0.60	5.2	5.9	4.35	5.625	5.516	18.5	Primarily for intermittent motion applications
488	42	375	40	22.0	4000	8.0	121	0.67	2.0	7.5	5.55	5.625	3.000	6.5	General purpose servo motor
488-HT	42	375	-	22.0	4000	8.0	121	0.60	2.0	7.5	5.55	5.375	3.125	8.5	Special motor for 750 °F. ambient temperature
668	140	1175	24	2.5	2500	10	145	0.52	8.0	16.5	12.2	7.125	2.531	13.0	General purpose servo motor
858	425	2250	20	.650	1720	16	161	0.46	10	30	22.2	9.000	3.375	25	General purpose servo motor
1028	1000	8400	20	.196	1500	22	161	0.46	20	56	41.4	11.00	4.719	57	General purpose servo motor
1028C	427	-	-	1.75	3000	25	161	0.48	16	19.3	14.3	11.00	1.625	16	Designed as mechanical power source
1028D	1000	8400	33	.234	1500	22	161	0.50	20	54	39.6	11.75	5.875	77	Dual armature machine for velocity & position servos
13510	2160	8600	-	.07	500	20	201	0.60	60	108	80.0	14.88	12.50	160	Low speed high precision velocity servomotor
19524	450	900	-	.08	500	3.5	577	1.55	20	144	107	19.00	3.000	-	Design operating speed 1 revolution per day
5008C	450*	-	-	.474 x10 ⁻³	120	162	163	0.10	-	2.78*	396	50.00	5.250	2000	Industrial servomotor: speed 4.5 rpm

*lb.-ft.

TABLE I

where S is the maximum operating speed in thousands of rpm and D is the armature diameter in inches. Details relating to the armature structure, air gap clearances and internal motor damping, if any, usually modify this relationship. However it is useful as a general guide and, taken with the similitude relationships for continuous rated torque, indicates that the continuous shaft horsepower output for a printed motor increases as the square of the motor diameter.

In summary, experience to date as reflected by Table I encompasses a wide range of ratings and operating conditions:

Generation of rated torques up to 450 lb.-ft.

Feasibility of operation is ambient temperatures of 750 degrees F.

The possibility of mechanical time constants as low as 1×10^{-3} seconds in internally damped low speed machines.

Operating speed ranges in direct drive under servo control from 7×10^{-4} rpm to 4000 rpm.

Operating Experience of Lifetime and Reliability

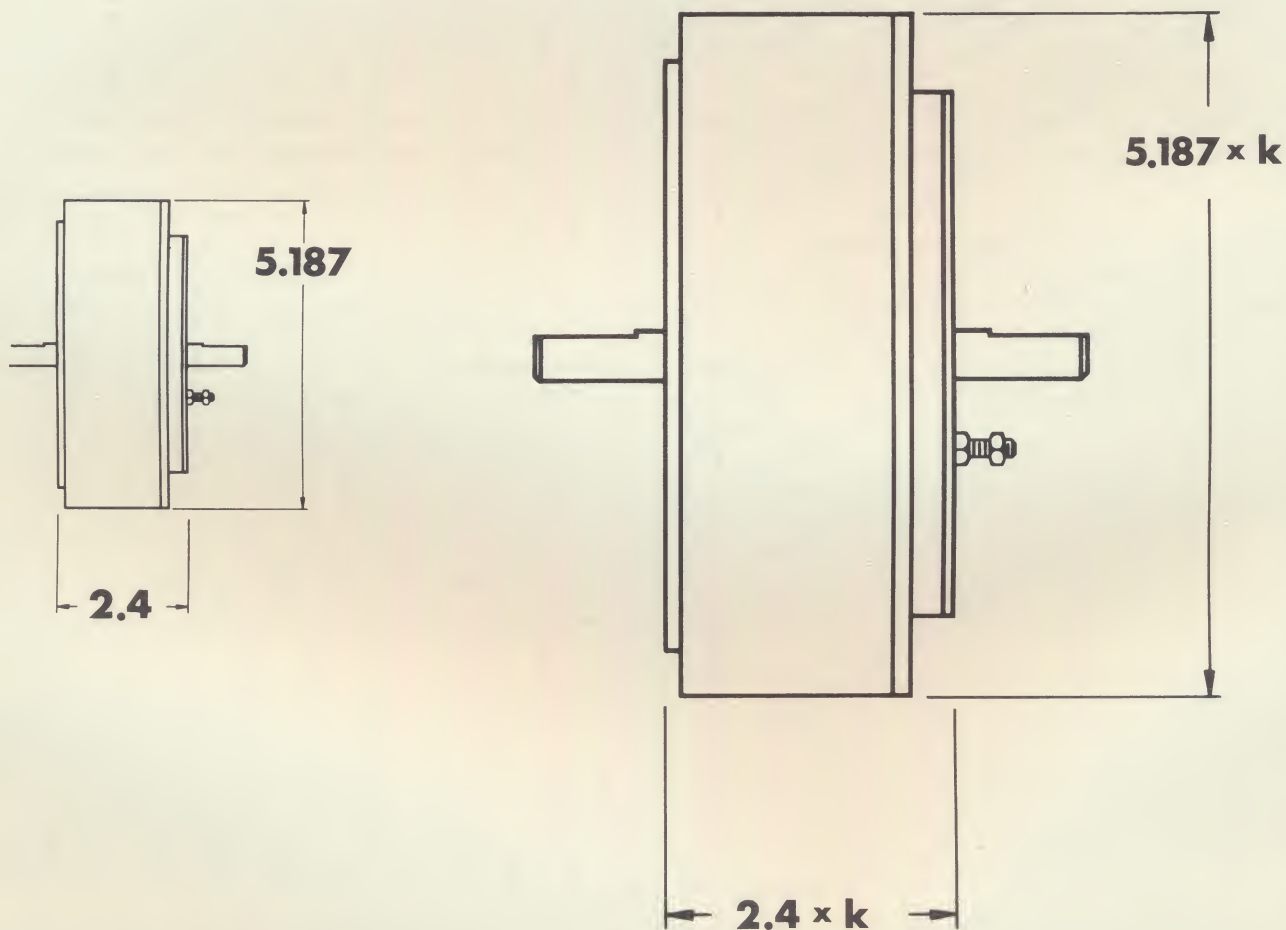
It will be recalled that one of the important mechanical features of the printed motor is that no separate commutator is used. Instead, the brushes bear directly upon the uninsulated copper armature conductors. Since the copper is not more than a few thousandths of an inch thick in small machines, a question has frequently arisen regarding lifetime and reliability performance in the area of brush and commutator (or armature) wear. What lifetimes can be expected?

A second and more or less related question arises from the fact that because there is no rotating iron, the thermal capacity of the printed armature is low in small machines and similarly, the thermal time constant under stall conditions is short. Is the printed motor a delicate and tricky device to work with?

Experience shows that both of these questions can be

Figure 4

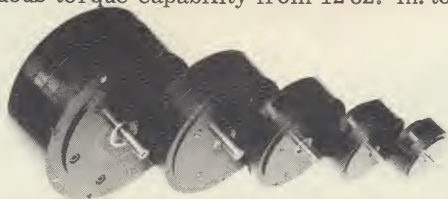
Variations in machine parameters as a function of size may be predicted from geometrical similitude ratios by assuming that all dimensions are related by a factor k while holding flux density and number of armature conductors constant.



answered in a satisfactory manner. Lifetimes of thousands or tens of thousands of hours for the armature can be easily achieved depending on the operating conditions. The motors are not delicate or tricky provided reasonable care is observed to stay within the published ratings. The latter statement is particularly attested by the fact that aside from normal production deliveries, hundreds of machines of all types have been shipped to many types of customers for evaluation in many different applications. Returns due to failures resulting from operation within the specifications have been virtually non-existent.

Figure 5

Models PM-368, 488, 668, 858 and 1028 range in continuous torque capability from 12 oz.-in. to 5 lb.-ft.



Perhaps the most important difference between the printed motor and its conventional counterparts results from the fact that nature does not confer the machine advantages without exacting one important penalty. This is that if a destructive accident occurs the armature in small machines may be damaged to the point where a repair is impracticable. Fortunately, however, the remedy is quite simple since the entire armature disc may be replaced with less effort than is involved in resurfacing a conventional commutator.

For normal environmental conditions the brush material utilized in printed motors is approximately 50% silver-50% graphite. Other additives are used in certain cases. Life tests have shown that optimum wear performance is obtained at a brush pressure of about 4.5 lbs. per square inch. Either lower or higher values result in more rapid brush wear and commutator surface erosion, although any value in the range from 4.0 to 5.3 psi is satisfactory. Proper preparation of the commutating surface is also important to obtain flatness and a smooth surface finish. In larger machines this is accomplished by actually machining the commutating surface of the finished armature assembly. There is no requirement for mirror-like smoothness. In practice, a finish of 12 to 15 micro inches is perfectly satisfactory. In all machines it has been found desirable to support the brush track with a radial extension of the mounting hub on the reverse side of the armature.

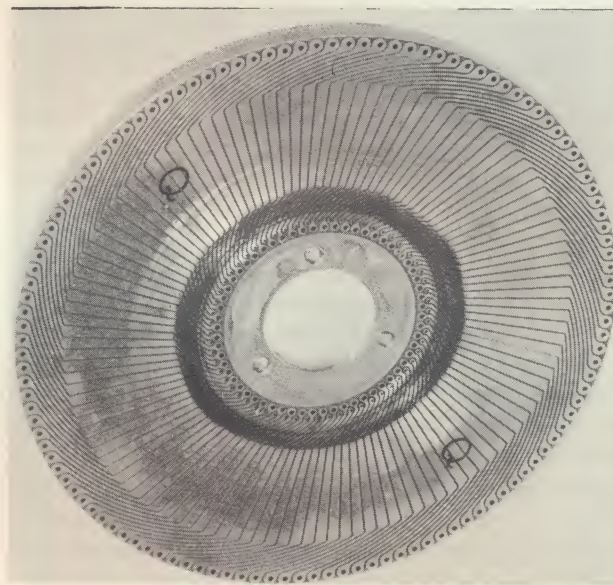
Operation of small machines such as the type PM-368 at a speed of 3000 rpm produces brush wear at an average rate of 0.040 inches per 1000 hours. This figure results in part from the fact that commutation conditions in printed motors closely approach DC slip-ring operation. The stored inductive energy is negligible. Since the brushes are relatively short

with limited spring travel, brush replacement and maintenance of the motor about every 3000 hours is indicated for continuous operation at these high speeds. Wear of the armature itself takes place at a very low rate, as is the case in any properly designed commutating system. Sections of armature conductors have been examined with a metallurgical microscope to determine actual copper erosion. The data indicates that small armatures should operate through several brush changes and that a life expectancy of a minimum of 10,000 hours exists for small machines when operating at maximum rated speeds. For larger motors the situation progressively improves since the maximum operating speed is reduced more rapidly than the commutation rate in feet per minute is increased due to the larger commutation diameter. In addition, the thickness of the copper armature conductors increases at a rate which is roughly proportional to the diameter.

Continuous maximum speed operation of printed motors is a rarity by virtue of their almost universal application in servomechanisms. An alternative and

Figure 6

Armature for Model PM-488 machine showing brush track and commutating region after 1200 hours of operation at 3000 rpm.



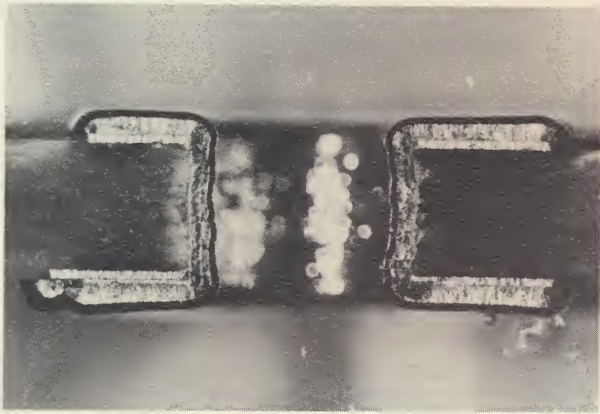
useful estimate of brush life may be obtained by computing the time necessary for the machine to make between 5×10^8 and 10^9 turns. For a large servo motor operating at 200 rpm this calculation predicts a life time of about 80,000 hours. For low speed operation the life expectancies soon become sufficiently great to be of no practical significance.

Occasionally a question is raised on the reliability of the plated-through hole connections which are presently used in connecting between conductors on opposite sides of the armature. Although this technology is not well known in the electrical machin-

ery industry, it has been exhaustively studied and documented by a number of agencies in relation to the printed circuit component industry. The reliability index of the plated-through hole is particularly impressive when the hole configuration is of the type to be found in the printed circuit armature. Suffice it to say that the total number of connections made by this simple and automatic method in all of the printed circuit armatures to date lies between one and two million, and that as yet, not one machine malfunction has been attributable to the failure of a plated-through connection.

Figure 7

Sectional microphotograph of plated-through hole used for side-to-side connections in printed armatures.



Two models of the printed motor, types PM-368 and PM-488 have been tested for vibration and shock behavior under the military specifications MIL-E-5272 C and MIL-E-5472C. No physical or electrical degradation was observed following these tests.

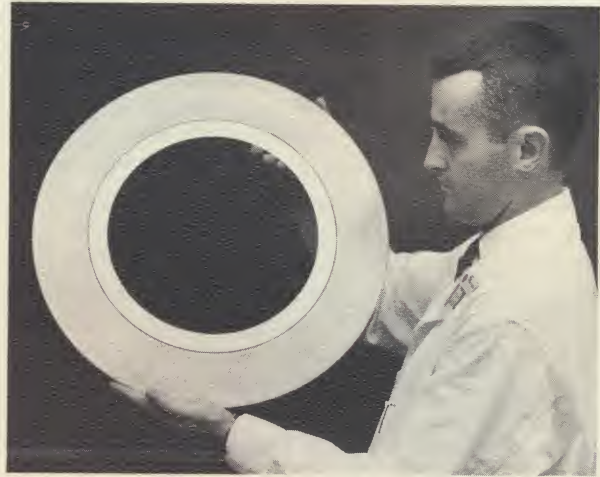
To summarize, the most important single factor which determines the lifetime and reliability of the printed motor is the commutating process. The characteristics of the printed armature require that the commutating system be designed with considerable care in that material, brush pressures and brush rigging must be properly selected for the service. However, when this task is properly performed, the motor is perfectly satisfactory in wear and reliability performance and is entirely competitive with conventional machines.

Unique Properties

The printed motor geometry is basically that of a short cylinder or pancake whose thickness varies with the requirements of the field structure. This is a definite innovation for design engineers who are accustomed to the cylindrical arrangement of conventional machines. Furthermore, the printed motor is of little interest in those applications which now utilize high speed motors of perhaps 1/2 inch diameter by one inch axial length.

Figure 8

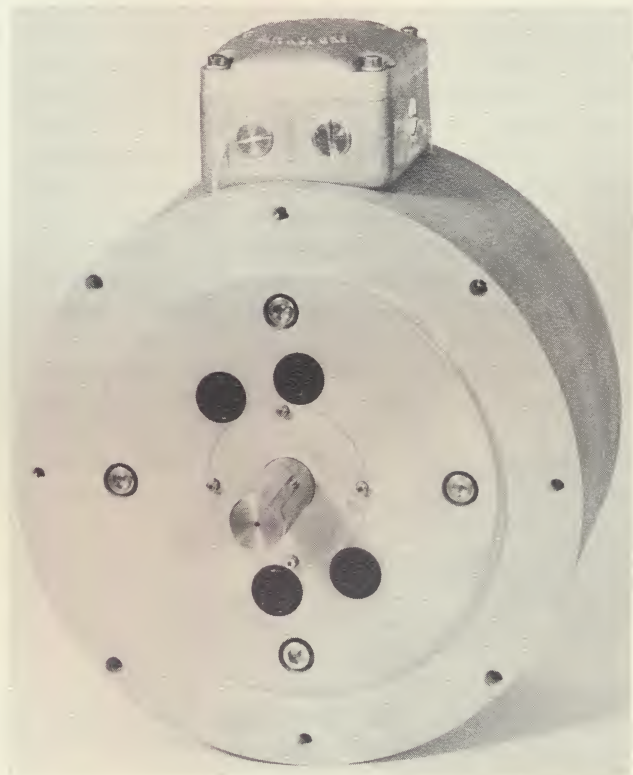
Armature for Model PM-19524 low speed servo motor designed for operation in direct drive under servo control at speeds down to one revolution per day.



However, a surprising number of applications have arisen in which the shape of the motor has been exploited to achieve a new and useful result. In particular, it is easy to design printed motors having large holes through the output shaft or motors of annular form. The PM-19524 listed in Table I is a

Figure 9

Model 1028D dual armature servo motor. Two electrically independent armatures turning in the same air gap are accessible through the four terminals on the motor case.



good example of this application. The motor is designed for operation under servo control at one revolution per sideral day and has an 11 inch clearance hole in the center of the armature for the hydrostatic bearing system.

In another design being manufactured to special order and not shown in the table, we find two mechanically independent printed armatures rotating within the field structure. Output is obtained from a coaxial shaft arrangement. Either armature may rotate in either direction at any speed, independent of the other.

In the Model PM-1028D we have a useful development in the area of servo machines. This motor contains two electrically independent armature windings laminated into a single armature disc. In application one armature circuit may be used to drive the machine and the other may be used as an integral tachometer. Alternatively, the power amplifier system may be simplified by using each armature to drive the shaft in opposite directions. In effect this machine may be considered as the DC analog of the conventional two phase AC servo motor with center tapped control field.

Figure 10

Model PM-488-HT is designed to operate at 750 degrees F. The motor case is fabricated from stainless steel. The armature uses high alumina ceramic as a base material.

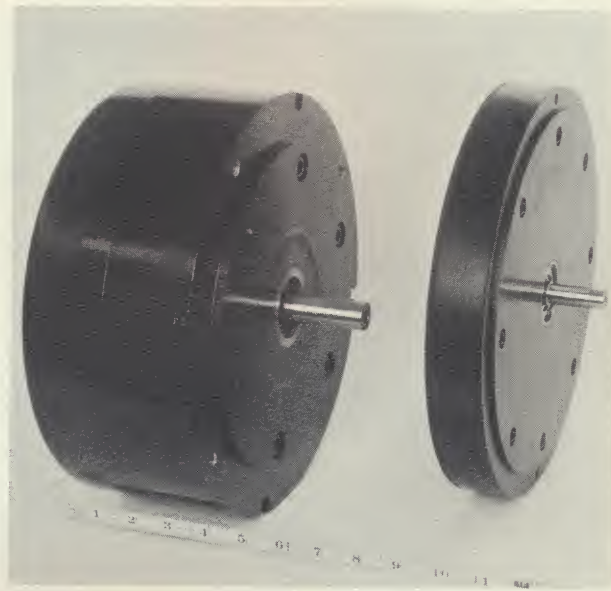


The type PM-488 HT motor utilizes an armature winding formed on a base material disc of high alumina ceramic thus producing a motor which will operate at ambient temperatures of 750 degrees F. or higher for periods which are now limited for all practical purposes by the life of the bearings. In this case we benefit from the independence of the armature windings from the magnetic field structure and by recent developments in printed circuit technology which would be virtually impossible to apply to conventional machine designs. In this connection it should be noted that our present effort in process research is directed toward armature designs for all types of printed motors which are completely free of organic materials. Realization of this goal will

permit substantially more liberal specifications on total machine dissipation.

Figure 11

Comparison of axial length between models PM-1028 and PM-1028C. Output from the flat machine is 950 watts at 3000 rpm.



Since the great majority of motor applications today are for servo devices, the magnetic field structure is made from alnico-type materials to obtain the highest possible flux density. These magnets require considerable axial length in the printed motor because of the large air gap. In applications where lower flux densities are feasible, an interesting class of motors results from the use of the new, high coercive force, oriented barium ferrite magnet materials. A typical example is the PM-1028-C in which a mechanical output of 950 watts (1.25 horse power) is obtained at 3000 rpm from a motor having a diameter of 11 inches and a axial length of only 1.625 inches. It should also be noted from Table I that the axial length (thickness) of the PM-5008-C design is only 5.25 inches for a torque capability of 450 lb.-ft.

Increasing application of inexpensive pancake type motors with ferrite fields in non-servo type applications is expected in the future. In this area we hope to realize upon the prospect of very low cost in fully automatic production.

Survey of Applications

Today's applications of printed motors in servo-mechanisms of course include control of both position and velocity. In addition, substantial use of the machine is made in a special class of service which is a mixture of position servo, velocity servo and stepping motor characteristics and which we call intermittent motion.

In position servomechanisms we find application in

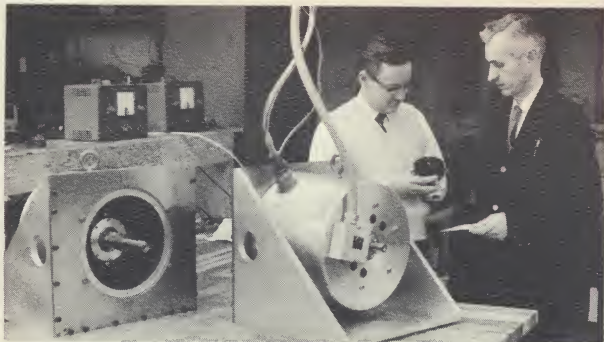
- direct drive of the lead screw of a numerically controlled machine tool to obtain improved repeatability of position over hydraulic or similar conventional actuators, to eliminate multi-loop servo systems, and to simplify the power supply problem. Models PM-488, PM-668 and PM-1028-D are used in this service.

- direct drive of X - Y traverse mechanisms in plotting devices to obtain improved accuracy and faster response over AC servo drives. This application is similar to numerically controlled machine tools. Models PM-368 and PM-488 are used.

- direct drive of computing potentiometers in analog computer multipliers to obtain faster response and higher accuracy. Frequency bandwidths achieved with the printed motor in this application are ten or more times greater than can be obtained from conventional gear motors. Small signal frequency response of 100 cps is easily obtainable. Models PM-368 and PM-368-HF are suitable.

Figure 12

Model PM-13510 high precision, low speed servomotor. Maximum continuous torque capability is about 10 lb.-ft. at speeds from 1 to 300 rpm.



In velocity servomechanisms we find applications in

- direct drive of the capstan of a magnetic tape recorder to achieve a wide speed range on the order of 120 to 1 without encountering speed flutter due to motor cogging at the low end of the range. Models PM-368 and PM-488 are used in this service.

- direct drive of the velocity control shaft or metering point in machinery for processing webs or filaments of material to obtain highly accurate speeds free from torsional noise disturbances at velocities from essentially zero to a few hundred RPM. In such applications the motor shaft speed typically remains constant within 0.1% measured over a few degrees of rotation of the

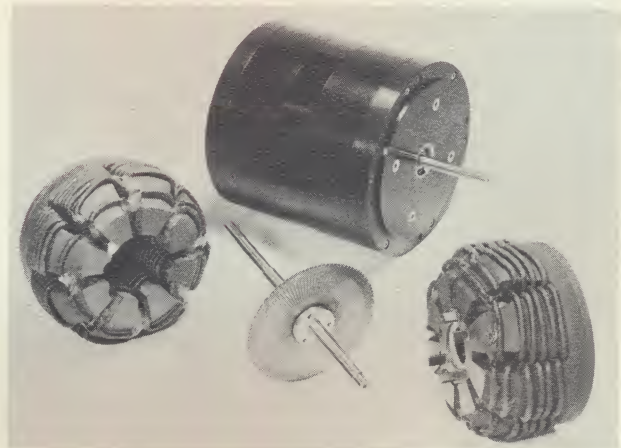
shaft in the presence of pulse torque disturbances of several lb.-ft. from the load. Models PM-1028-D and PM-13510-SS are used in this service.

- direct drive of low inertial loads at high speeds under conditions where output velocity must be modulated by a control signal with high frequency components to obtain fast response. Models PM-368 and PM-368-HF are typically used in this service.

For intermittent motion systems, a suitable example to illustrate the principle is provided by application of the motor as the capstan drive of a perforated paper tape reader. The operating requirement is that the tape drive system be able to advance the tape continuously at speeds of say 40 inches or 400 characters per second (the characters are spaced 0.1 inch on 1.0 inch wide paper tape). When a particular character is sensed by the reader the drive system must be able to stop the tape before that character has passed the reading aperture which is equivalent to saying that the tape must be brought to a stop from its normal velocity within a distance of about 0.020 inches. In addition, the drive system may be required to advance the tape one character at a time on command from some external signal more or less in the manner of a motion picture projector. Desirable operating speeds for the step-by-step mode of tape transport range upwards to 200 or more characters per second.

Figure 13

Model PM-368-HF high flux density motor. With internal damping, the mechanical time constant of this motor is 1×10^{-3} seconds or less.

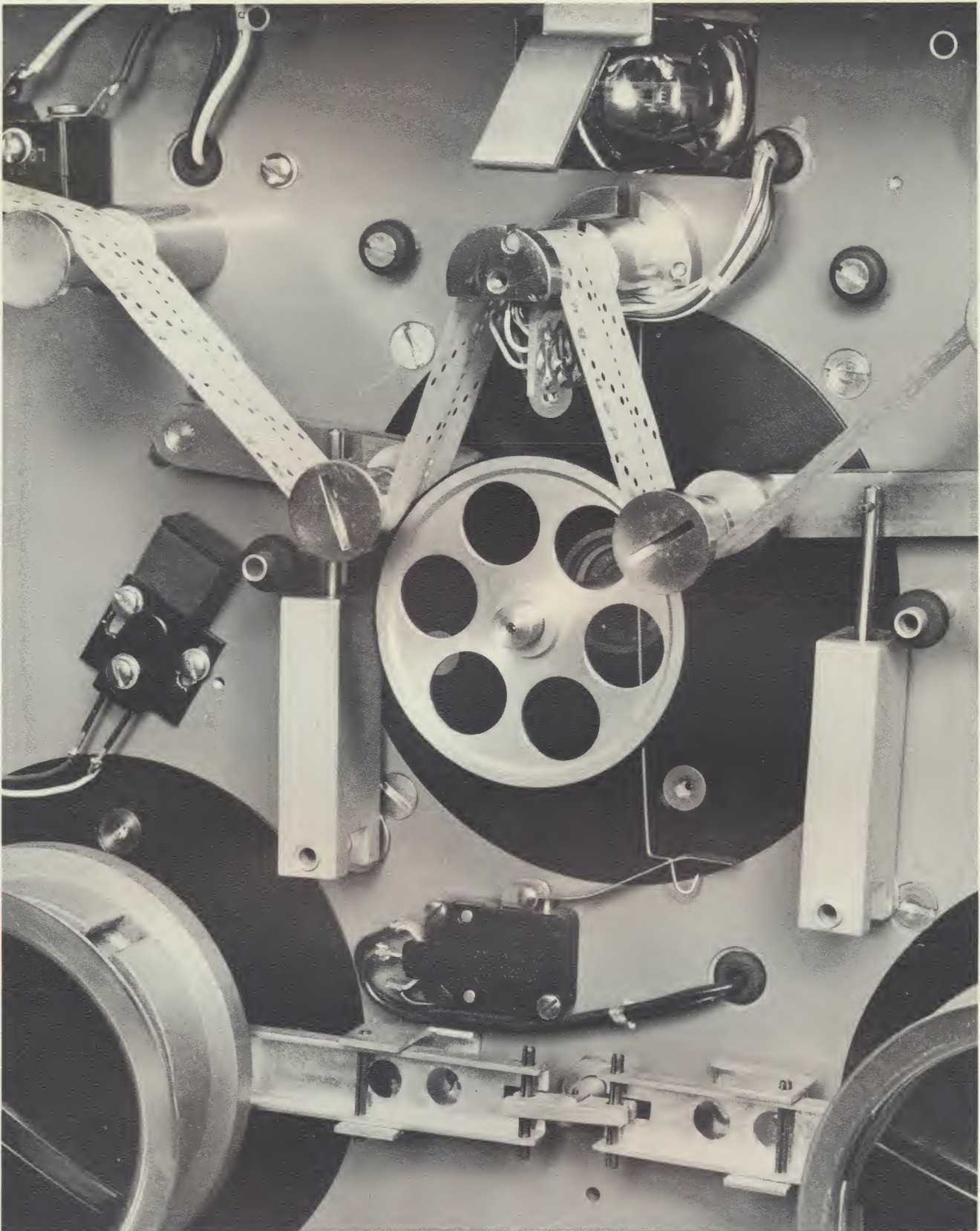


In conventional practice these motions are accomplished by a set of high speed clutches and brakes which may be made to function according to the requirements although frequent maintenance and adjustment are usually required. In addition the noise generated by such a mechanical system when stepping at the higher frequencies is considered objectionable in some environments.

The printed motor type PM-368-HF-11 is capable

Figure 14

Model PM-368-HF-11 drives paper tape in steps of 0.1 inch stopping between steps at speeds up to 300 per second.



of making 300 or more discrete stops and starts per second and is ideally suited to this application. In service the motor is merely started and stopped by semiconductor devices while the paper tape is held continuously in contact with the output shaft by simple ball bearing pinch rollers. No other mechanical components or actuators are required and no adjustments are necessary or possible.

It will be seen that the printed motor in this application displays many of the characteristics of a stepping device since when the operation is in the step-by-step mode the rotation of the motor shaft is such as to move the tape 0.1 inches for each input command pulse. However, it is important to remember that the movement of the motor shaft is entirely under the control of the input signal and that steps of 1, 10 or an indefinite number of characters on the tape may be made as desired.

A similar application is encountered when the motor is used to index the read-out head of a magnetic memory drum. In this service the operation of the machine again resembles that of a stepping motor except for the fact that the steps are of any desired duration on command.

Conclusion

Experience in development and application of the printed motor has given much insight into the potentialities and uses of the device and clearly points the way for further work. The central points which have emerged may be distilled into the statement made previously, to the effect that the motor as a servo-mechanism component, by virtue of the unique combination of smooth torque and low mechanical time constant, provides high precision and rapid response, particularly in applications where the motor is directly connected to the load shaft without intermediate gearing. Printed motors are capable of rendering superior service in a wide range of important applications with satisfactory reliability.

Future developments include further extension of machine performance, reduction in cost and exploration of promising new types of motors. Parallel programs are now under way in systems and power amplifier techniques to raise the performance capability of the power supply apparatus which is used as part of the motor system.

In summary, it would appear that a satisfactory proportion of the early expectations for the printed motor has so far come to fruition and that an as yet unlimited body of work lies ahead.

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